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SIMPLE METHODS AND INSTRUMENTATION FOR VERY SHORT EXPOSURE, HIGH REPETITION RATE KINEMATOGRAPHY IN CONJUNCTION WITH FLUID ATOMIZATION STUDIES

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HYDRAULISCHE MASCHINEN

FINAL REPORT

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Summary

The high voltage discharge of a pulsed light source with coaxial capacitor and extremely low inductance (Fischer-Nanolite) has been employed successfully for ultra-short-time exposure of rapidly changing phenomena in the boundary layer of two-phase-flow. By charging the coaxial capacitor from a much greater capacitor through a preset variable high ohmic resistor, light pulse series could be produced at a shot repetition rate up to 8 kcps. Due to the extremely short exposure time in the nanosecond range pictures could be taken without motion blurr on the quickly moving film, fixed on a rotating drum. Thus no rotating prism was necessary. Irregularities of the frame spacing, resulting from the time jitter of the discharge caused by its complex nature, do not seriously influence the evaluation of the projected pictures, but prevent motion pictures, which are highly desired, from being taken.

By triggering each single shot we succeeded in getting precisely timed repetition rates corresponding to the perforation rate. Design and operation of the electronic trigger-unit controlling high voltage discharge and shot series limitation are described. The triggering does not influence halfwidth and risetime of brigthness compared with free firing discharges up to frequencies of 20 kcps; higher values were not realized so far because of mechanical limitations and full utilization of 0,3 inch film size.

The rapid charging of the lamp capacitor at a rate of 4 kV/µs reduces the statistical jitter of the discharge sequence and therefore the jitter of the picture sequence will be smaller than the circle of divergence on the negative. The exact spacing of the exposures depends only on the exactness of the trigger pulses, which are supplied by a drum- or Fairchild-camera synchronized to the perforation of the film. The high speed cameras and the lighting device

developed in this way were used to investigate the atomization of liquids. Though the liquid particles are slowed down very rapidly after the detachment from the jet, high nozzle exit velocities are required. In order to study the disintegration itself it is necessary to get distinct exposures of particles in the order of some hundredth of a millimeter and velocities of more than one hundred meters/second. A simple calculation indicates that exposure times in the nanosecond range are required.

Contents

Symbols

C	Capacity
f	shot repetition rate
f_e	exposure repetition rate
f_p	projection repetition rate
I_1	current through the charging resistor
I_2	current through the arc
R_1	charging resistor
s_a	dimensionless absolute jitter of the discharge
s_r	dimensionless relative jitter of the discharge
t	time
t_a	charging time of pulse light capacitor
Δt	time jitter of discharge
U	voltage
U_o	voltage of power supply
U_z	breakdown voltage
ΔU_z	jitter of breakdown voltage
u_c	time-dependent voltage of the capacitor
d	diameter of liquid particle
D	nozzle exit diameter
f	vortex frequency
L	length of sensible film
m	exponent
n	number of exposures
s	path of a particle during exposure time
S	real length of image section
t_s	sojourn time of a particle within image section
T	interfacial tension
W	velocity
w_D	nozzle exit velocity
w'	turbulent fluctuation velocity
x	distance from nozzle exit or from the edge of the plate
$\mu 1, \mu 2$	dynamical viscosity of the disperse and continuous phase
ν_1, ν_2	kinematical viscosity of the disperse and continuous phase
ϱ_1, ϱ_2	density of the disperse and continuous phase
Re	Reynolds number
We	Weber number

1. Introduction

This is the problem set by the Contract:
"To investigate the possibilities of simple methods and instrumentation for very short exposure, high repetition rate kinematography in conjunction with fluid atomization studies".

The observation of fast, nonreproducible motions of minute, nonluminous objects requires special optical arrangements. High jet velocities are necessary, for instance, near the nozzle exit in fuel atomization processes. Sharp pictures with motion blurr not exceeding 5 % of droplet diameter require exposure times in the order of 10 to 50 ns.

Therefore the following methods of investigation are unsuitable:

1. Gas discharge lamps with energy consumption only during the exposure time. Even highly developed modern constructions with special composition of gases have a disturbing current tail; light intensity would be sufficient.

2a. The mechanical shutter can not realize aperture times required if only a continuous lighting device is available.

2b. Hitherto Kerr-cells were not tested thoroughly for technical applications. The trigger arrangement would surmount the range of simple methods. All systems of shutters utilize only a fraction of the luminous flux and require lighting devices which are practically impossible to be realized.

2c. Image converters only supply a small number of exposures. Also the low resolving power of the screen would not be satisfactory for observing the motion of small particles.

The best survey of modern developments is given by the

publications of the High-Speed-Photography-Congresses [1].

The high voltage discharge seemed to be most suitable. Here the consumption of energy is also restricted to the moment of exposure. H. Fischer, Airforce Cambridge Research Laboratories, Bedford/Mass., USA., developed coaxial capacitor light sources having halfwidth in the range of 10 to 30 nanoseconds. Their usefulness has already been demonstrated with single light shot photography of fast moving nonluminous objects [2].

The research problem is to modify the trigger system of the pulse light source for shot series with variable repetition rates in order to develop a high speed kinematography device with the possibility of motion picture observation.

Steps of the technical performance.

1. A film on a rotating drum is used for shot sequences. The distances of the individual exposures are not constant; they are only defined by a mean value. Therefore, these sequences cannot be presented by motion pictures.
2. A frequency control system synchronized with the perforation enables one to produce films which can be presented by regular motion picture projectors and evaluated with commercial equipment. The realization of this principle includes the possibility to trigger the pulse light source by high speed cameras.

2a. The film length is limited to one circumference of the drum. Start and stop of a shot sequence has to be determined exactly to prevent a second cycle or further cycles of exposures. The constant velocity of the film (circumferential speed of the drum) during the whole sequence is of great advantage. A 30 μm circle of divergence and a 30 ns effective exposure time would permit a circumferential speed of 1000 m/s without any motion blurr. Since it is impossible to manage this speed practically, an optical picture compensation is absolutely unnecessary.

2b. With an increasing demand of film length the construction of drum cameras becomes more and more difficult to handle; therefore commercial cameras with their larger capacity can be used. Besides the advantage of exposure times in the nanosecond range there may be a disadvantage in special cases due to the relatively low frequency of only 5000 to 8000 pictures per second attainable.

We decided to go both ways in order to get a maximum of versatility at each stage of development in the investigation of fuel atomization.

2. Physical basis

2.1. The pulse light source

Assuming constant capacity, the brightness of the arc increases with decreasing discharge time and increasing breakdown voltage. The whole discharge time depends on the sum of all reactances.

Data of the light-source:

capacity	3,5 ... 5.10^{-9} F
breakdown voltage	3,5 ... 5,5 kV (air of lat)
inductance	1.10^{-9} H
arc lenght	0,8 ... 1,2 mm
current rise	$2,3.\ 10^{9}$ kA/s
maximum current	2,5 kA
current density	$1,3\ .\ 10^{5}$ kA/cm^2
engergy of pulse	$5,4\ .\ 10^{-3}$ J
maximum light intensity	18.10^{6} sb
maximum brightness	$1,2\ .\ 10^{5}$ HK
halfwidth	30 ns

Construction details of the light source are shown in fig. 1. The time jitter of several single shots was less than 0,2 ns. For further details see the publications of H. Fischer [3,4].

The spark gap characteristic, i.e. current as a function of voltage between the electrodes, not only depends on the construction, i.e. geometry, but also on several physical variables:

kind of surrounding gas,
pressure and temperature (molecular velocity distribution),
influence of radiation,
polarity of electrodes.

The influence of time is in so far important as a fast voltage rise, dU/dt, during the charging of the coaxial capacitor, shifts the statistical jitter ΔU_z of the breakdown voltage to higher mean valuess of U_z. We suppose that the first exposure of each sequence will be overexposed because of the relatively high breakdown voltage of the first shot. The dielectric strenght of the coaxial capacitor has ta be high enough to withstand this first shot. The time function of the voltage on the capacitor during the charging is generally given by

$$u_c\ (t) = U_o\ (1 - e^{-t/R_1 C}) \qquad (1)$$

U_o means the voltage of the power supply supposed to be constant, C the capacity and R_1 the charging resistor. The jitter of the breakdown voltage U_z causes a fluctuation in the time intervals between the discharges, which corresponds to a fluctuation in repetition rate. The minimum time fluctuation within the linear range of the characteristic is given by, see fig. 2,

$$\Delta t_{min} = R_1 C \frac{\Delta U_z}{U_o} \qquad (2)$$

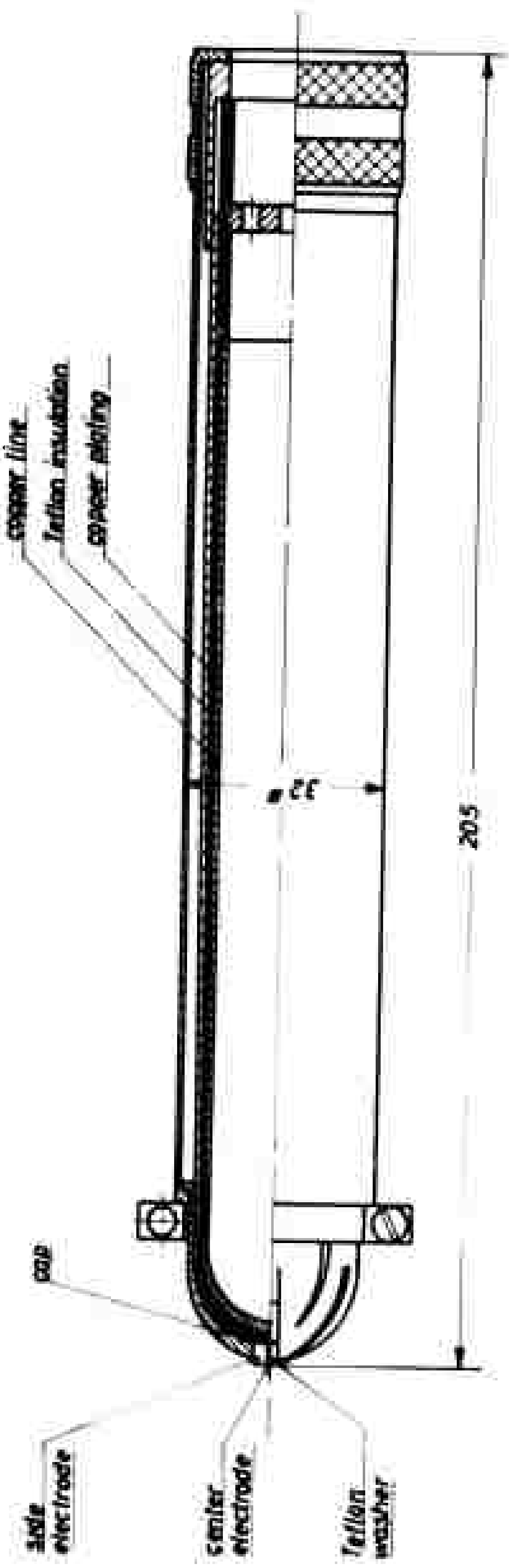

Fig.1. Fischer-Nanolite

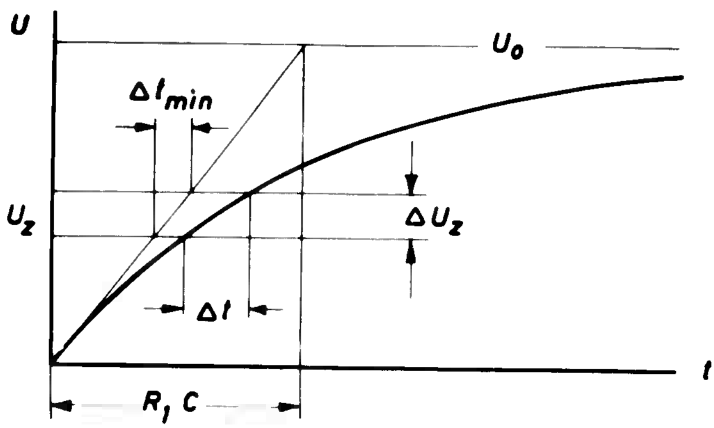

Fig. 2. Charging of a capacitor

The general equation includes not only the relative jitter $\Delta U_z/U_z$ but also the rate U_z/U_o. The linearized form of the equation can be written

$$\frac{\Delta t}{R_1 C} \approx \frac{\Delta U_z}{U_z} \cdot \frac{U_z/U_o}{1 - U_z/U_o} \qquad (3)$$

The time jitter is proportional to the jitter of breakdown voltage, if the voltage jitter ΔU_z is much smaller than U_z. Only in the nonproportional range can the time jitter Δt be reduced by reducing the rate U_z/U_o, this means enlarging of U_o, which may be difficult and expensive.

2.2. Free firing and timed shot sequences

The free firing untriggered shot sequence needs the total time interval t_A between two shots to charge the coaxial capacitor. Hence

$$t_A = 1/f, \qquad (4)$$

if f is the shot repetition rate of the sequence. In the case of timed shot series the charging time is restricted to a fraction of the interval between two shots, hence

$$t_A < 1/f. \qquad (5)$$

The relative jitter of free firing shot sequences is

$$s_r = \Delta t/t_A, \qquad (6)$$

i.e. the rate of the unavoidable statistical jitter Δt and the charging time t_A is equal to the absolute jitter

$$s_a = \frac{\Delta t}{1/f} \qquad (7)$$

Triggering each shot, on the contrary, extremely decreases the observable displacement S_a of each exposure because of the shorter charging time required.

Fig. 3 demonstrates the schematic arrangement. The shot repetition rate of free firing sequences results from the time constant R_1C, switch S closed. If timing is required, on the contrary, it is done schematically in closing switch S for each charge and opening it after each breakdown.

Fig. 4 shows schematically the characteristic curves of u_c (capacitor voltage), I_1 (current at the charging resistor). For timed shot series additional trigger and cut-off pulses are necessary to actuate switch S, which are also shown in fig. 4. If the charging current I_1 is not turned off externally, the arc extinguishes only if the maximum value of I_1 does not exceed the minimum of I_2 required to maintain the burning of the arc, hence

$$I_1 \max < I_2 \min \qquad (8)$$

From this condition there results a maximum realizable repetition rate f_{max}. Combining the charging equation (1), $I_{1\,max} = U_o/R_1$ and $u_c = U_z$ at the moment of breakdown, there follows

$$f_{max} = \frac{J_{2\,min}}{U_oC\left[-\ln\left(1-\frac{U_z}{U_o}\right)\right]} \qquad (9)$$

This limiting frequency is proportional to the minimum current maintaining the arc. In a more detailed consideration inductances must also be taken into account.

Comparing the 2 principles it is evident that the essential disadvantage of the free running circuit is the statistical

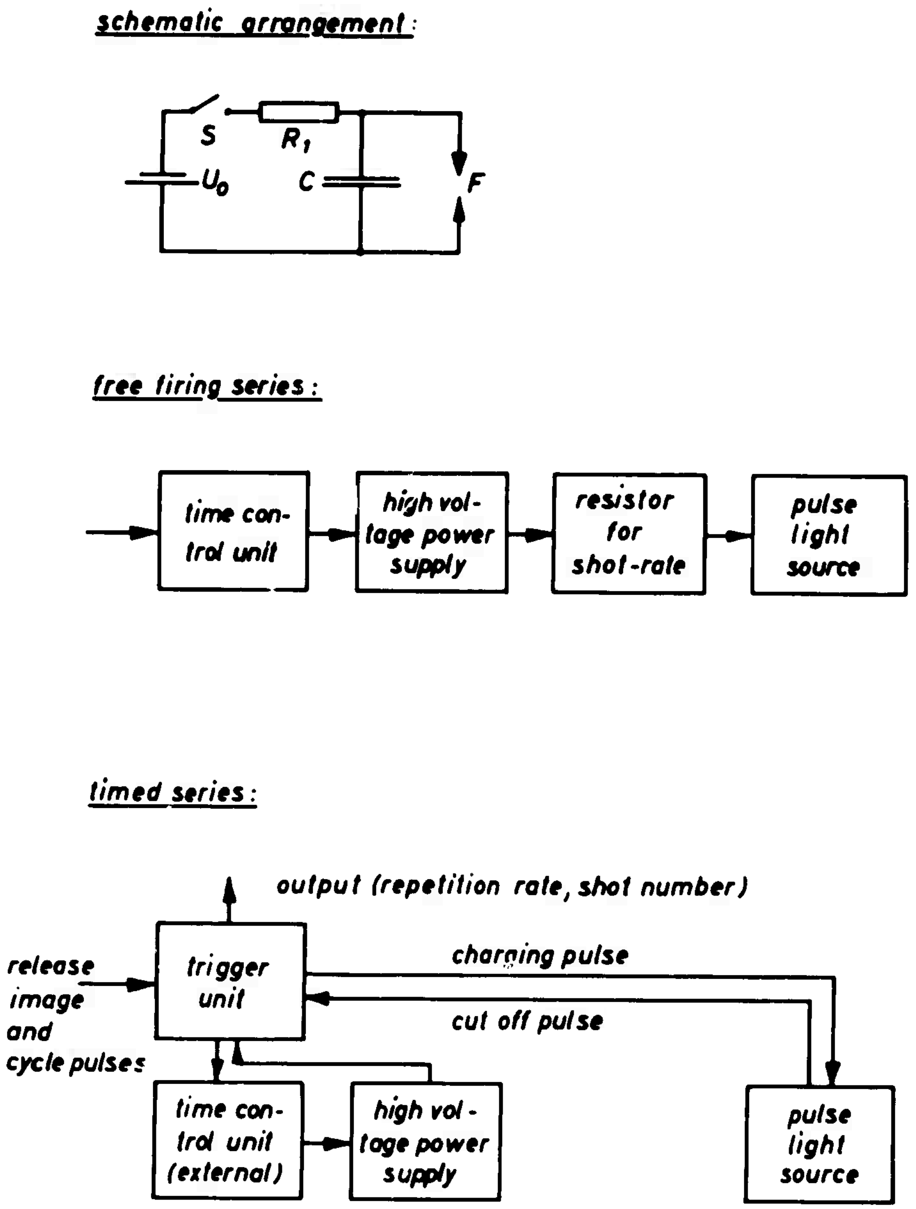

Fig. 3. Schematic arrangement and block diagram

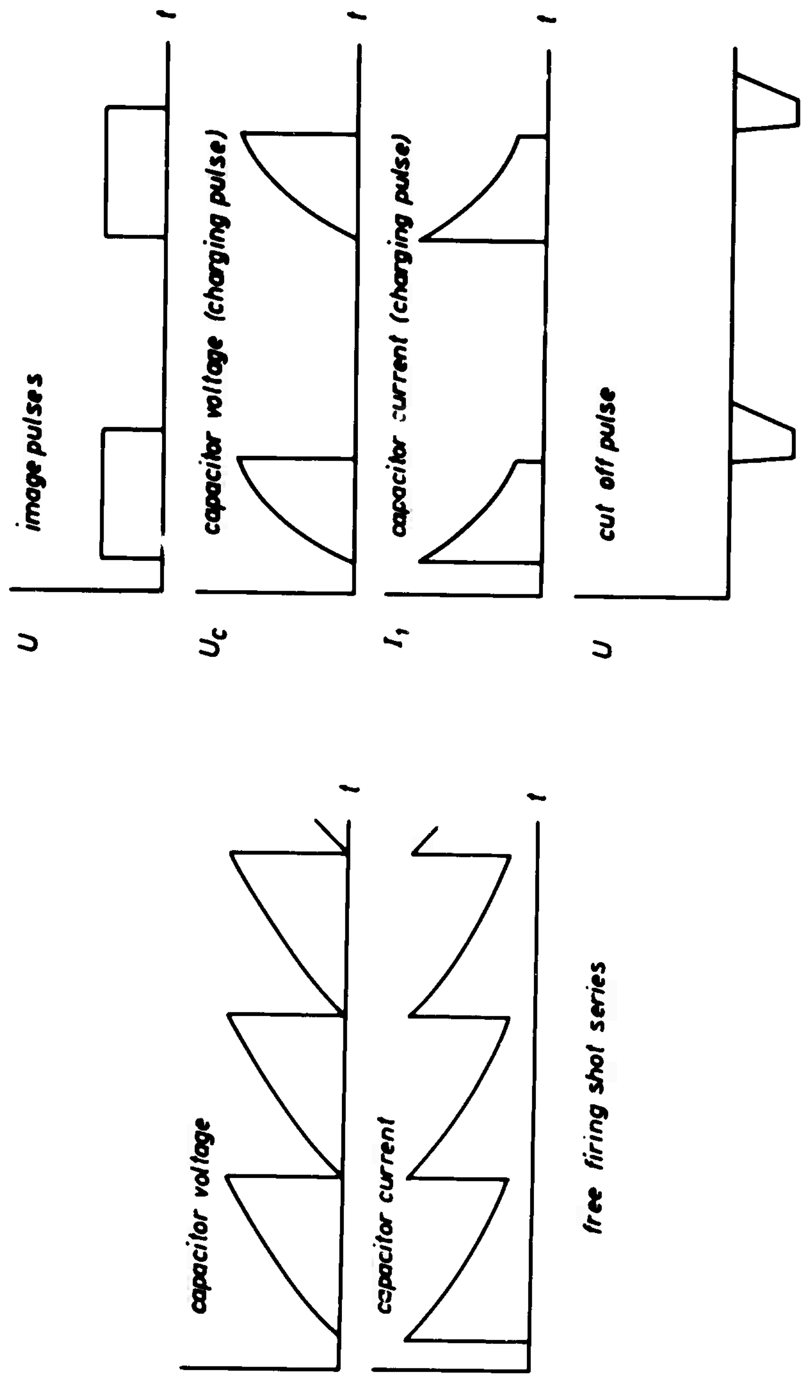

Fig. 4. Scheme of Pulses

jitter of the shot intervals (equal to the exposure intervals), and the fact that the arc, once ignited, burns continuously if the charging current exceeds a critical value - thus restricting the repetition rate to low values. With the developed arrangement 8 kcps. were realized. The outstanding feature of the second principle, the timed series, is the actuating of the switch S for each shot, i.e. the charging current is turned on and cut off externally. Now the power rate of the electronic switch determines the limit of shot repetition rate; in principle values in the range of 100 kcps. should be realizable.

A pulse repetition rate of 10 kcps. corresponds to an interval of 100 μs, and a maximum relative jitter of 20 %, for example, sponds to 20 μs. If the absolute jitter should not surmount 1%, the charging time must be restricted to only 1/20 of the interval; that means 5 μs in this case. Proportional to the restricted charging time a decrease of absolute jitter results:

$$s_a = s_r \cdot t_a \cdot f \tag{10}$$

The moment of breakdown is now defined more exactly but fluctuates statistically as much as before around a mean value. Therefore it can not be recommended to fix the moment of the turn-off of the charging current. It is much better to initiate the turn-off by the discharge of the capacitor itself, by causing the falling edge of the voltage to turn off the switch S. In addition trigger pulses are required to close it. From the point of view of practical applications a controlled start and stop of the whole series is also desirable. It is self-evident that only electronic methods can be used, especially in the range of high repetition rates and short shot series.

3. Construction

Remark: Since the equipment was developed only for laboratory purposes any patent claims have been disregarded.

3.1 Free firing shot sequences

The elements of the arrangement, see fig. 3, correspond to the following units:

power supply	Uo	high voltage power supply
switch	S	timing control unit
charging resistor	R_1	resistor cascade
capacitor	C	pulse-light-source
spark gap	F	

3.1.1 Timing control unit

The variable number of revolutions of the drum camera requires a limitation of the shot sequences within the time interval of 30 to 500 ms. At t = 0 a saw tooth generator is triggered, see fig. 5. The saw tooth itself triggers an electronic switch (Schmitt-trigger). The slope of the pulse varies the duration of closed circuit condition. This duration can also be preselected externally.

3.1.2 High voltage power supply

The rectified high voltage can be varied steadily in the range of 0 to 10 kV. The voltage doubling circuit consists of 2 capacitors, 0,5 μF each, and of 2 cascades of diodes equipped with protective and discharging resistors in parallel. A choke (15 Henry) and a capacitor are used to smooth the voltage. Before and after the firing of shot sequences a high-voltage-vacuum-relay shorts the circuit, thus removing the residual charge from the capacitors. The continuous rate of the power supply amounts to approximately 200 W, thus limiting the repetition rate of permanent running shots. During a short time shot series the repetition rate can be increased to ten

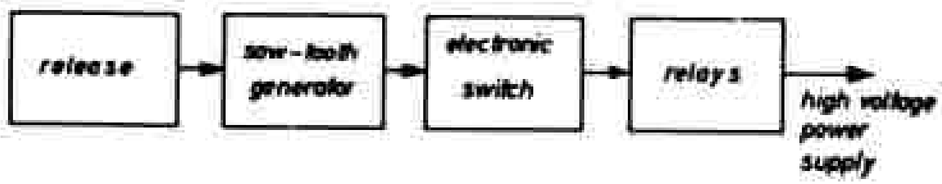

Fig. 5. Timing control unit (block diagram)

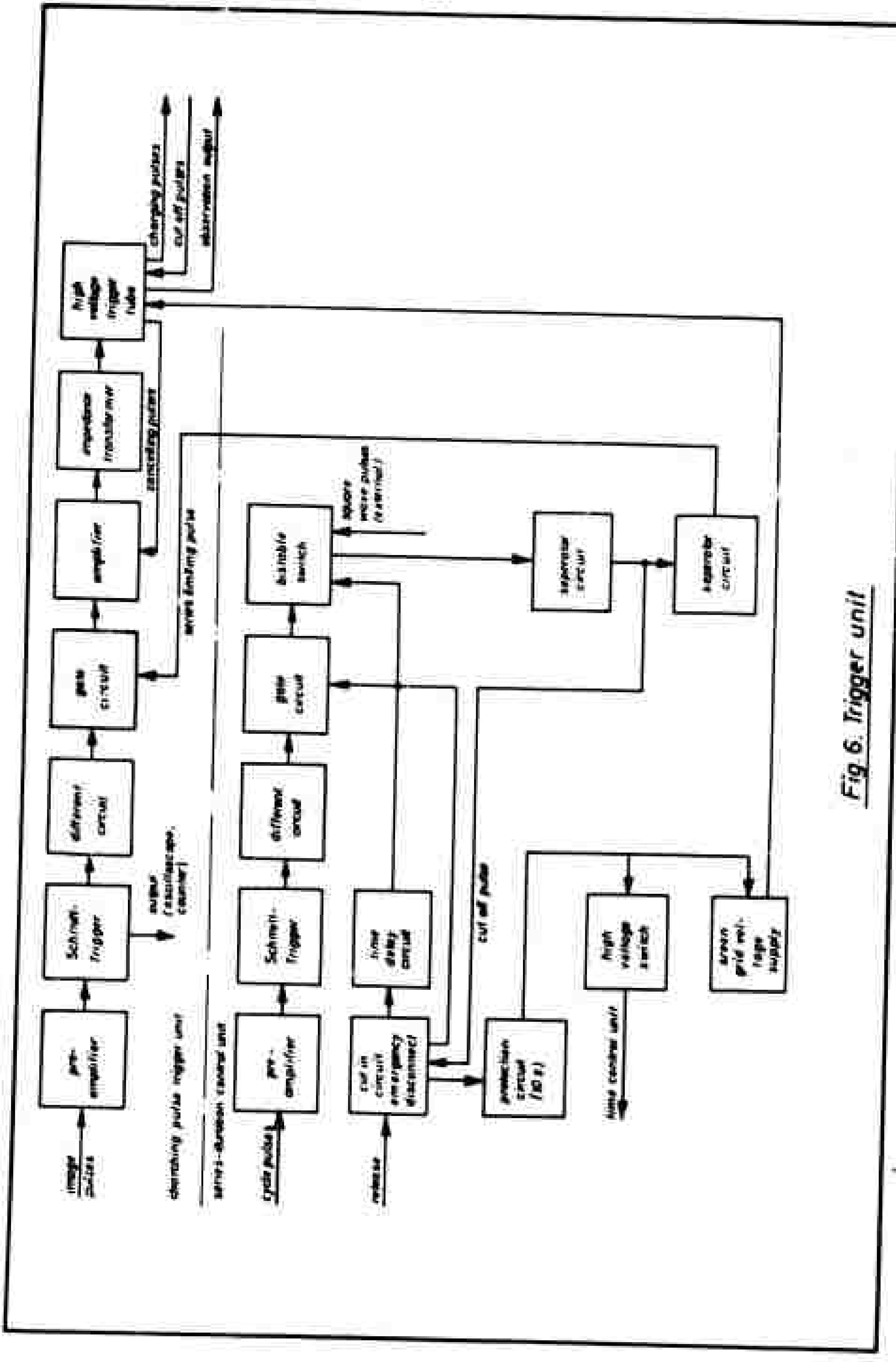

Fig 6. Trigger unit

times this value.

3.1.3 Control of repetition rate

Varying the time constant enables one to control the repetition rate from about one shot up to several thousand shots per second. This can be performed only by adjusting the charging resistor, because the capacity of the light source is a fixed value. A calibration curve represents the function of the repetition rate versus the charging resistor with constant charging voltage U_o.

3.2. Timed shot series

In the block diagram, fig. 3, a trigger unit now replaces the charging resistor cascade. The time control unit is actuated externally. An additional capacitor (6 μF) is required in order to balance the high voltage power supply output, especially for high repetition rates.

3.2.1 Trigger unit

This equipment consists of charging-pulse trigger unit and series-duration control unit, see fig. 6.

Charging-pulse trigger unit

This unit operates independently from the shape of pulses. This shape is also permitted to vary during a series, but the amplitude has to be at least 1 V (peak to peak). The amplified pulses (image pulses) are fed into a pulse shaping circuit (Schmitt-trigger). A differentiating circuit converts the square wave pulses with their fast leading edge to positive and negative needle shaped pulses. Only the positive ones can reach the succeeding circuits, provided that the gate circuit has opened. There the pulses are shaped to square pulses of 6 μs pulse width; this corresponds to

the maximum time required to charge the flash capacitor. A voltage step originating from the break-down cancels out the pulse and prevents thereby a further charging. A voltage amplifier and an impedance transformer circuit follow. They amplify the charging pulses up to 1 000 V, and a current of 1 A can be drawn. This power is required for efficient control of the succeeding high voltage trigger tube, which corresponds in principle to switch S.

The time interval of 5 μs between the rise of the charging pulse and the breakdown of the spark gap results in a delay of 5 % in the case of 10 kcps pulse repetition rate; the percentage decreases with lower pepetition rates. If the image pulse is adjusted 2,5 μs in advance in the favoured range of repetition rates, the time lag between release of the shot and the best frame position is diminuished to zero for these conditions.

Series-duration control unit

The time limitation of series requires trigger circuits for high voltage and screengrid voltage of the high voltage trigger tube. At a set-time after the moment of release the following cycle pulse of the continuously running series will start shot series and the next one will stop them and cut off all high voltage circuits. All further cycle pulses must have no effect. The first circuits are constructed in principle in the same way as the first part of the trigger unit: preamplifier, Schmitt-trigger, differentiating and gate circuit. As soon as the equipment is ready to work, all actions are started by actuating the release switch which then immediately turns on the voltage and a little later the gate circuit of the timing unit. The gate circuit is succeeded by a bistable switch, which turns on by the first cycle pulse let through, and turns off by the next one. Turn-on-duration corresponds to the gate pulse width transmitted to the trigger unit.

The falling edge of the gate pulse is used to restore the original state of the whole apparatus. Assuming that shot series starts but does not stop (in case of lacking cycle pulses) after about 10 s an emergency disconnector circuit is actuated.

Instead of the method described above also the bistable switch of the series-duration unit can operate directly by means of positive square wave pulses fed to the input.

4. Supplementary equipment

4.1. Pulse generators

It is possible to apply the line frequency (5 cps, period 20 ms) to limit the shot series and also to use the calibration frequency of an oscilloscope instead of other image pulses. A square wave generator, however, delivers pulses of variable repetition rate. The human voice can be considered as a series of image pulses with variable pulse width and interval corresponding to the coordination to discontinuous phenomena. Performance check using a microphone with amplifier came off satisfactorily.

Pulse generators of the drum camera

Two commercial inductive pulse generators, commonly used to measure the number of revolutions, are mounted in the casing of the camera, see fig. 7. The image pulses are coordinated to the perforation spacing of the film by means of radial grooves in a thin iron ring, the number of the grooves being the same as that of the exposures arrangeable on the circumference of the drum.

Pulse generator of the Fairchild-High-Speed-Camera HS 101

By request the supplier installs an optical pick-up. Slits mounted on the sprocket wheel open the path between a lamp

and a photodiode. A transistorized amplifier (developed by us for this purpose) raises the pulse voltage up to 1 V (peak to peak).

4.2 Electronic counters

A counter, Beckman/Berkeley Model M 7360, indicates the exposure repetition rate as soon as the image pulses are delivered to the trigger unit by the drum.

A double preset counter, Beckman/Berkeley Model 7425, was used for the following functions:

1. Test: The square wave generator delivers image pulses to the trigger unit and to the preset counter. Together with the release of the trigger unit the preset counter is reset to zero. The first preset adjustment corresponds to the product of image pulse repetition rate and time required to charge the high voltage capacitor (0,3 s). The total number of shots is determined by the second preset adjustment. This method can be employed generally in all cases requiring an exact time delay between the start of the shot series and the moment of release, and if the event does deliver a special signal to limit the shot series.

2. Cooperation with the Fairchild-Camera: The optical pickup delivers pulses as soon as the sprocket wheel begins to rotate. During the acceleration period of the camera a considerable part of the whole film length available is consumed, especially in the case of high final picture repetition rates. If 5 m sensible film are sufficient to catch the event, exposure of 25 m of trailer film during the acceleration period would waste the energy of the capacitor and speed up the fatigue of the high voltage trigger tube unnecessarily. The first preset is adjusted therefore corresponding to the trailer length. The high voltage capacitor is charged during the acceleration period. The second preset corresponds to the length of sensible film and avoids further shots.

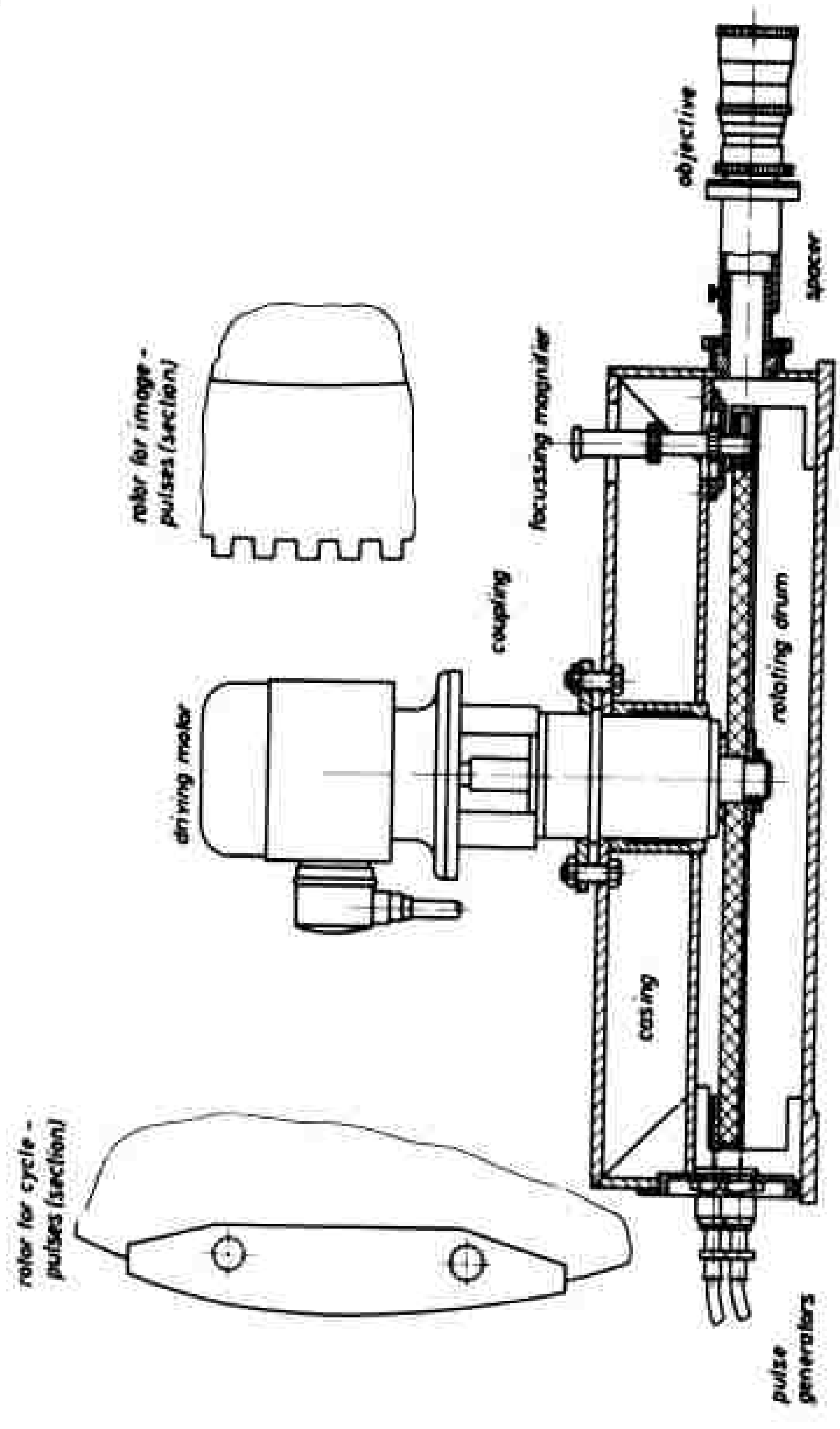

Fig.7. Drum camera

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5. Mechanical and optical components

5.1 Experimental set-up for atomization

It is not necessary to describe details; essential data are considered to be sufficient. A piston pump is driven by a spindle; suction and pressure stroke are released independently. The nozzle exit velocity can be varied in a range of 1:1000 up to 160 m/s, by means of different piston speeds and piston and nozzle exit diameters. Hydrodynamical considerations resulted in the selection of two nozzle modifications; a nozzle with a smooth cylindrical hole and a nozzle with an intensely contracted cross section at the exit. Geometrically similar shapes were manufactured in a range of 0,5 to 4 mm nozzle exit diameters. The influence of physical properties (density and viscosity of the two phases and their common interfacial tension) on jet disintegration can only be studied by atomization of numerous liquids (e.g. water, different oils, amylalcohol, mercury) and by variation of the continuous phases, liquids (insoluble in the disperse phase) and gases (air, hydrogen, carbonic acid) of different pressures. The experimental set-up satisfies to reach rapidly a steady liquid motion. Electromagnetic couplings control the piston motion and the piston itself turns on a switch adjustable along the stroke, assigned to start further motions.

5.2 Lens system

The lens system collects and directs the light to the object. A modification in the coaxial arrangement improves the quality of exposures: A half reflecting mirror deflects a part of the light to the side. This light is then reflected by a second mirror to the object, also lighting the object from the side; lighting from the side alone would be insufficient.

5.3. Cameras

During the first stage of development single exposures demonstrated the extraordinary usefulness of the Fischer light source. There were some advantages of standard film material (24 x 36 mm). In the case of the same image size of the object and of the same sensibility of the film the section exposed is considerably larger than using substandard film (16 mm). These investigations were already mentioned [2,5].

5.3.1. Drum Camera

The drum camera has been constructed for laboratory purposes only, see fig. 7. The problem of triggering each shot by an image pulse required only the installation of some further parts. The application of Fairchild-Camera objectives with great light transmitting capacity, spacers, reflex view finder system and film size (16 mm) was obvious. The circumference of the drum corresponds to 200 normal sized exposures. A D.C.-motor is required, at least for untriggered sequences. Up to a centrifugal acceleration of 2000 g (20000 m/s^2) it is sufficient to stick the free ends of the film with some prestress. Two light-proof covers, not represented in fig. 7, close the camera housing. The little inconvenience of taking the pictures in a darkened room nevertheless made it unneccessary for us to develop a suitable shutter triggered by the cycle pulses.

5.3.2. Fairchild-High-Speed-Camera HS 101

Essential data:

16 mm substandard film, film capacity 30 m, range of picture frequency 200 to 7500 pict./second. Exposing time markers on the film supplies the time base. A time delay between the start of the camera and turning-on of a further switch in order to release an event can be preset steadily in the range of $\pm$ 2,5 s.

6. Operation of the total arrangement

A single switch puts the arrangement into action; this means the electrical and atomization set-up. Three working modes are given and some modification suggested.

6.1. Free firing shot sequences (drum camera), fig. 8 a

The adjustment of the charging resistor and the circumferential speed of the drum result from the chosen jet velocity and size of the image section. The time control unit is adjusted for the time of one revolution of the drum. The available film capacity is utilized better if the time of the shot series is adjusted a little longer than the time of one revolution, since the first shots are then superimposed with some afterburning shots.

After the electromagnetic coupling between driving motor and the piston pump is turned on, the piston transports the disperse phase, jet disintegration begins almost immediately, only delayed by compressibility and elasticity of the pressure cylinder and conduits. The time control unit is turned on by the piston itself running over a contact. This unit turns on the high voltage power supply, and after approximately 50 ms the shot sequence starts. After the preset time has elapsed the charging circuit is cut off.

6.2. Timed shot series (drum camera), fig. 8 b

The number of revolutions of the drum is an exact measure for the shot repetition rate chosen from the point of view of the jet disintegration study. After the same procedure as described above the trigger unit cuts in, a pulse is forwarded to the series duration control unit, which cuts in the charging of the high voltage capacitors.

After the charging time has elapsed the next cycle pulse delivered from the camera starts the shot series; the shots themselves are triggered by image pulses. The following cycle pulse (after one revolution of the drum) cuts off shot series and charging voltage.

6.3. Timed shot series (Fairchild-High-Speed-Camera), fig. 9

Corresponding to a calibration curve the D.C. voltages for the motors of the camera are adjusted. The time the trailer length requires to run through, dependent on final picture frequency, determines the succession of the start of the camera and of the start of the trigger unit which can be adjusted by means of the camera control unit. The first preset of the counter depends on the trailer-length, the second one on the length of the sensible film.

After the start of the piston pump the camera control unit is cut in by the piston contact, hence the trigger unit and the camera cut in. The pick-up pulses are forwarded from the camera to the trigger unit and to the preset counter, which summarizes these pulses up to the first preset number, then the shot series starts, and the second preset cuts off the series. The end of the film starts the braking of the spool motor. The second counter indicates the real number of the fired shots.

Modifications:
The preset counter, employed as a simple program controlling unit, and the time delay circuit of the camera control unit make it possible to vary the succession described above. This will be necessary if the event lasts a shorter time than the acceleration period of the camera. Then the camera control unit or the first preset circuit has to start the event later than the camera. The second preset can stop shot series.

7. Discussion of methods and results attainable

Before reporting the atomization research in the following chapter, applicability and productivity of the different photo-

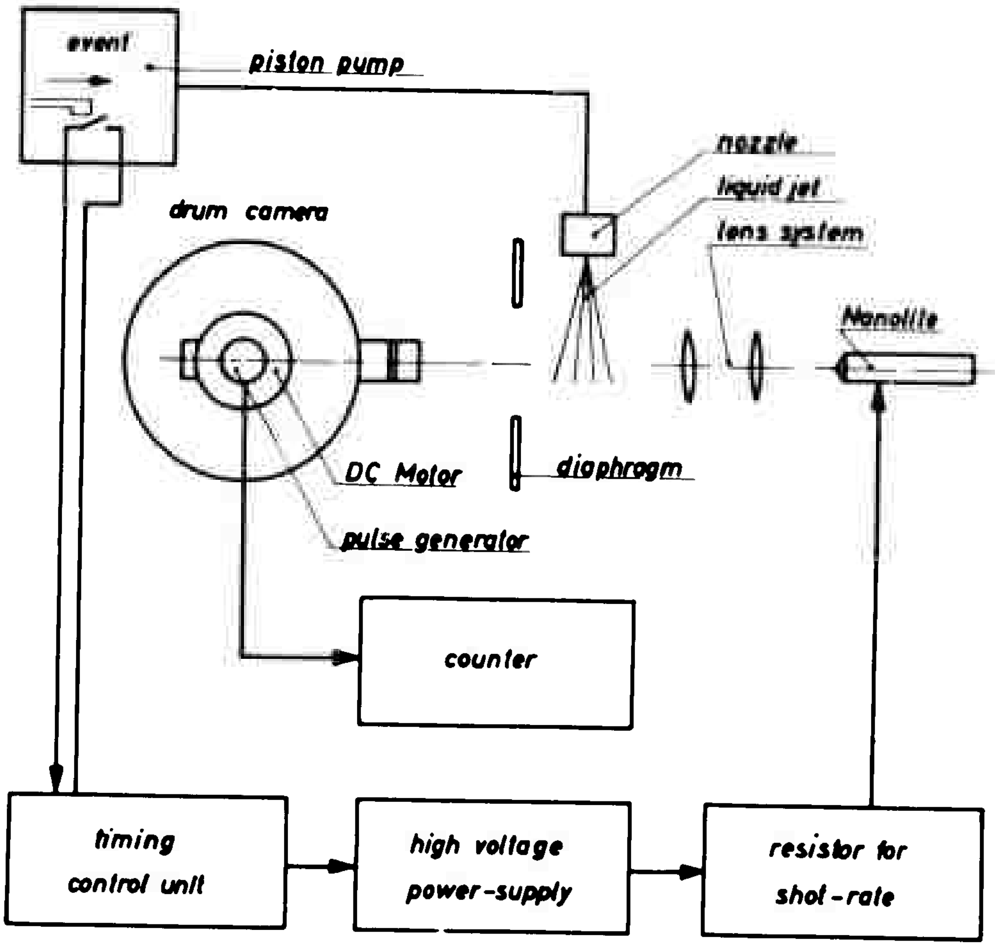

Fig. 8a. Drum camera and free firing shots

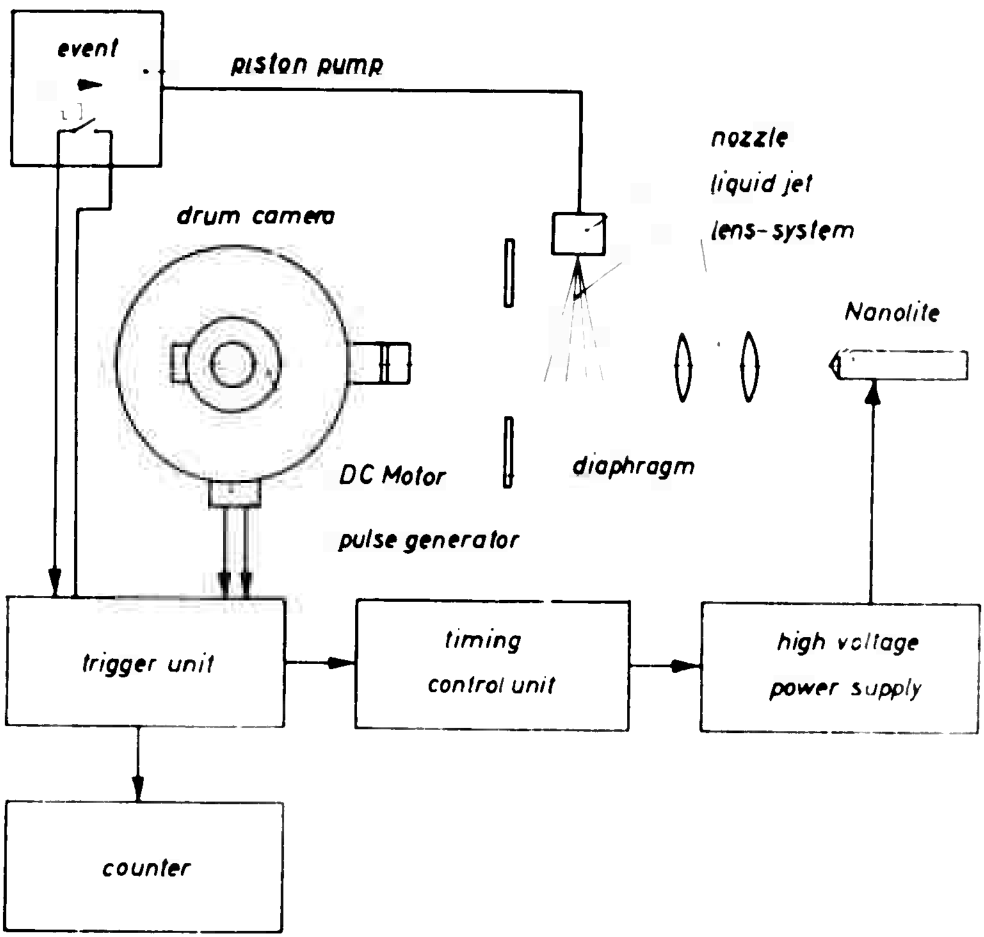

Fig.8b. Drum camera and timed shot series

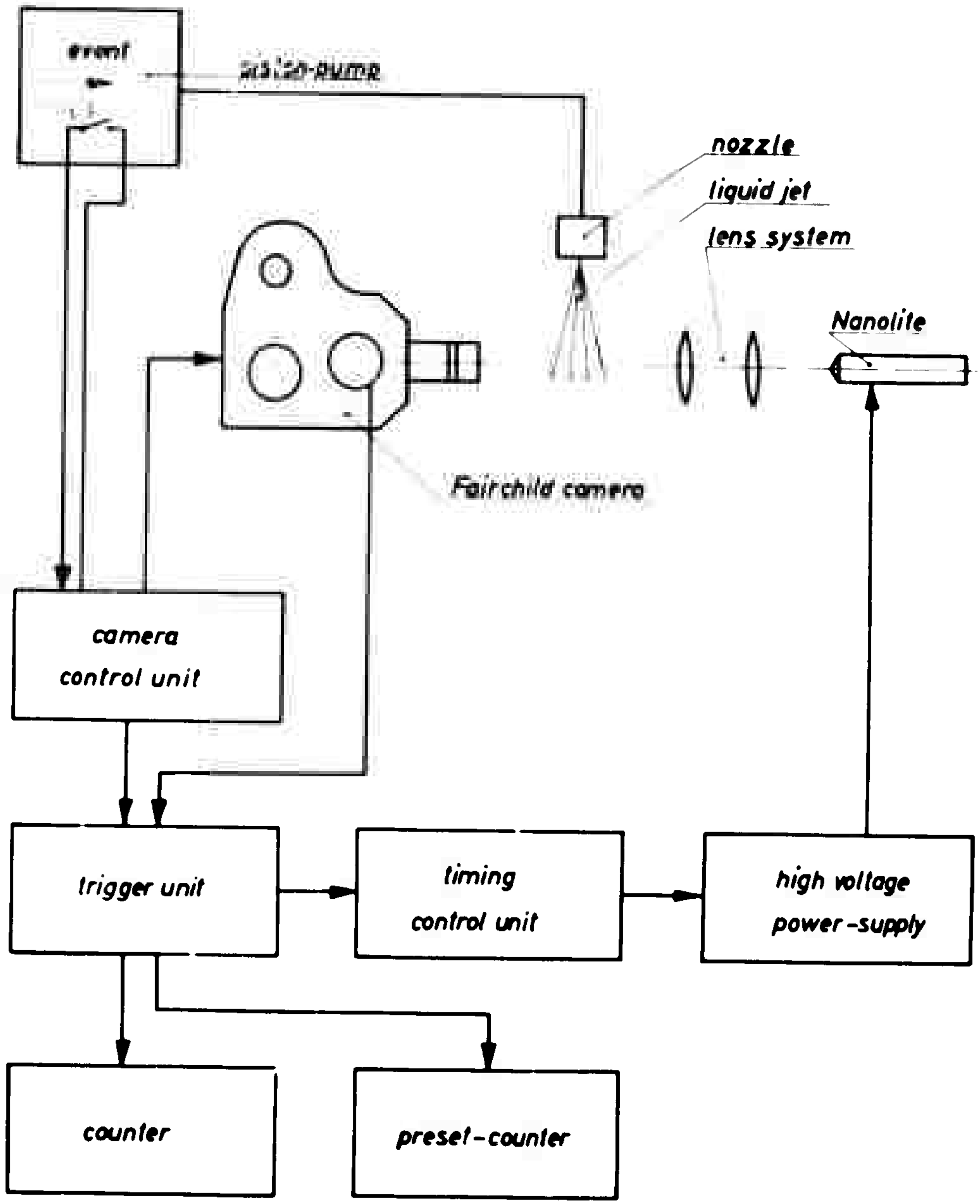

Fig.9 Fairchild camera and timed shot series

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graphical methods may be compared (single exposure, free firing sequences, timed series unable to be presented and timed series able to be presented by motion pictures). We will discuss the problem in general and refer to the problems of jet disintegration in the case of numerical calculations. Jet velocity can be substituted by any rapid motion and the diameter of droplets by another geometric dimension of the process under investigation. In the case of generalization one has to pay attention to the following fact. The disintegration of high pressure liquid jets belongs to the nonreproducible, unstationary phenomena following Schardins classification of high-speed-photography [6]. Only statistical mean values can be considered reproducible and stationary, but they are not sufficient to get real insight into the physical mechanism.

Assuming a particle of d = 0,02 mm diameter with a velocity of w = 40 m/s and a relative motion blurr s/d = 10 % permissible, the exposure time Δt required for a single exposure will be

$$\Delta t = \frac{s}{d} \cdot \frac{d}{w} = 50 \text{ ns} \qquad (11)$$

The size S of the object depends on the resolving power of the film material, depth of focus attainable and therewith on the chosen scale.

The single exposure catches the jet at an arbitrary moment. Repeated single exposures improve the physical comprehension and provide mean values suitable for certain measurements. In principle, statements are impossible concerning local velocities. For this reason the spectrum of droplet diameters evaluated by this method does not represent the real droplet flow. The particle in question stays in the image section of a length of S = 50 mm for a sojourn time of

$$t_s = S/w = 1{,}25 \text{ ms.} \qquad (12)$$

n = 8 may be sufficient, if the number n of exposures during this time is only chosen from the point of view to evaluate deformations and local displacements. Hence the exposure repetition rate is

$$fe = \frac{n\,w}{s} = 6400 \text{ exp./s} \tag{13}$$

Hence the film length L consumed for n exposures, exposure spacing equal to perforation spacing provided (N = 131 exp./m), is

$$L = \frac{n}{N} = 61 \text{ mm} \tag{14}$$

Since the free firing exposure sequence renounces the coordination to perforation spacing, the length of film required for n exposures may be larger or shorter by reason of any image width permissible.

The same conditions hold true for timed exposure series if motion picture presentation is not desired, which of course can be realized in this case by an expensive copying procedure in order to adjust exposure spacing. In principle, the fluctuation of exposure distances does not prevent the evaluation of deformation velocities and velocity distribution of the disintegrating jet.

The production of motion picture films has to take into consideration the projection frequency fp in the range of 16 to 25 pictures per second. Artifices may be excluded as e.g. the repeated copying of the same exposure, one beside the other. The duration T of one motion picture scene which is still perceivable as a continuous movement results in an exposure number of $n_s = T \cdot f_p$. Assuming a mean value T = 3 s and f_p = 20 pictures/s n_s will be equal to 60 exposures. Hence the exposure repetition rate must be

$$f_e = \frac{n_s\ w}{S} = 48\ 000\ \text{exp./s.} \qquad (15)$$

$$t = \frac{L_{max}\ N}{f_e}\ , \qquad (16)$$

which is proportional to the reciprocal value of exposure repetition rate.

Summarizing, films of fast motions (fast moving particles) able to be presented by cinematographic methods require extremely high repetition rates of exposure, exceeding the range of moving film. With the film free from motion blurr it is already possible in the realized range of repetition rates to get an impression of the phenomenon which remains completely undist rbed from the procedure of measurement. The presentation of motion pictures supplies qualitative results rather quickly. On the other hand the evaluation of exposure sequences projected as diapositives - the only possibility in the case of free fired sequences - needs more time but delivers quantitative results which are always finally desired.

8. Survey of the fluid atomization studies

8.1. Object of research

The purpose of the investigation did not consist in the development of an atomization process; such a task would be a technological problem.

This study concerns the fundamental question: What is atomization, of what kind is the physical mechanism of liquid atomization? Numerous fields of application do not impair the fundamental importance of this question.

Some differences of technical methods may be suggested. High nozzle exit velocity (straight or swirl jet) requires high pressure. Mechanical devices and vapour or gases in the function of an expanding third component are often expensive. Jet disintegration itself is a hydrodynamical phenomenon in all cases. A liquid, the disperse phase, emerges from an orifice, mostly a nozzle fitted with a round outlet, and mixes with the surrounding medium, the continuous phase. The characteristic quantities are the geometric shape of the nozzle, the output and the physical properties of the components. The multiplicity of methods of investigation proposed and realized with more or less success and different theories led to an immense number of publications, see for instance K.J. DeJuhasz' survey [7]. Classic research and almost all theoretical work put the forces caused by the surface tension in the foreground.

1936 P.H. Schweitzer discussed the relationship with turbulent flow [8]. He cited experiments of jet disintegration under vacuum and pointed out the influence of nozzle boundary layer. No further research in this direction has been published, although obviously the spreading of an atomized liquid within a continuous phase (gas or liquid) resembles the turbulent extension of a subsonic gas jet.

H. Fischer's pulse light source together with suitable equipment was considered to be a good instrument for studying the relationship of jet disintegration and turbulent mass transfer.

The following quantities were evaluated from single exposures and exposure sequences:

1. The ranges of the different modes of liquid disintegration depending on jet velocity, physical properties of the components and geometric shape of the nozzles.
2. Laminar-turbulent transition length (distance from nozzle exit) of the free boundary layer indicating the start of turbulent jet disintegration and mixing.

3. Wavelength and stirring-up coefficient of disturbances.
4. Velocity distribution within the mixing region.
5. Fluctuations and irregularities resulting from the turbulent nozzle boundary layer.

8.2. <u>Discussion of some results</u>

The research confirmed the figures of jet disintegration chiefly controlled by capillary instability at low nozzle exit velocities, see fig. 10. The relative velocity of both components should be taken into account, restricting known theories, since the relative velocity diminishs essentially the influence of density ratio. The limits of stable disintegration figures following Haenlein[9], disintegration by capillary waves (Zerwellen), smashing (Zerschmettern) and atomization (Zerstäubung), can be presented for approximately constant density ratio dependent on the dimensionless group $\mu_1/\sqrt{\varrho_1 DT}$, containing physical properties and nozzle exit diameter, and Weber number $We = \varrho_1 w_D{}^2 D/T$.

The velocity distribution at the nozzle exit is found to be an independent quantity of the problem, but depending on the output and the geometric shape of the nozzle. The Reynolds number alone is not sufficient to characterize the flow; Fig. 11 demonstrates a qualitative difference between jets emerging from a cylindrical or contracted nozzle. This fact has special importance for the attempt to elucidate jet disintegration from the point of view of turbulence research. The influence of dynamical surface (interfacial) tension is restricted to the establishment of the interface beginning at the nozzle exit and to effects concerning detachment, deformation, motion and coagulation of disintegration particles. The behavior of turbulence velocity components (quantitatively given by the intensity, scale and spectra) in the mixing region of a free subsonic jet and in fully developed pipe flow has been published by Laurence [10] and Laufer [11] for instance. Disperse phase flow emerging

from a cylindrical nozzle of a sufficient length of constant cross section corresponds to the turbulent pipe flow at the exit. In the case of contracted nozzle cross section, the turbulent velocity components arise steeply within a small annulus accompanied by enormous shear rates, which then decrease in the diverging mixing region. Pipe tu bulence on the other hand with maximum values near the wall guarantees the existence of turbulent fluctuations over the whole cross section. The mixing region arises with smaller shear rates because of the accelerated thicker boundary layer. The statistical fluctuation velocities are the propulsive power for jet disintegration, starting in the unbounded flow. At small basic velocities and at low turbulence level (contracted nozzle section) the exchange of mass starts only after laminar-turbulent transition, recognizable at the interface. Fig. 1c represents clearly this essential difference. The undisturbed jet length not only depends on viscosity and density ratios but also in a decisive way on the mass ratio of disperse and continuous phase. That means that the physical mechanism varies, if one exchanges the components. Concerning theoretical considerations the principle of affinity is not valid, which also does not hold true for turbulent flow in the neighbourhood of the nozzle.

The ratio of capillary pressure and turbulent pressure fluctuations delivers a diameter of equilibrium of detached liquid particles in the magnitude observed. Choosing, for instance, a mean jet velocity of 50 m/s, a fluctuation intensity w'/w_D of only 10 % - maximum values are considerably larger - and water as disperse phase, there follows from

$$d_{droplet} = \frac{8\ T}{\varrho_1\ w_D^2\ \left(\frac{w'}{w_D}\right)^2} \qquad (17)$$

a droplet diameter of 0,025 mm.

A first disturbance of the smooth interface can be recognized as a wave with little amplitude. The unarranged detachment of

a b

Fig. 10. Jet disintegration by capillary forces.

a. Mercury jet into water b. Oil jet into air

Nozzle exit velocity: (a) 1 m/s, (b) 6,5 m/s
Nozzle exit diameter: (a) 2 mm, (b) 4 mm

a b

Fig. 11. Comparison of two jets emerging from a cylindrical and a contracted nozzle. Glycerine jet into water.

a. Cylindrical nozzle b. Contracted nozzle

Nozzle exit velocity: 0,55 m/s
Nozzle exit diameter: 2 mm

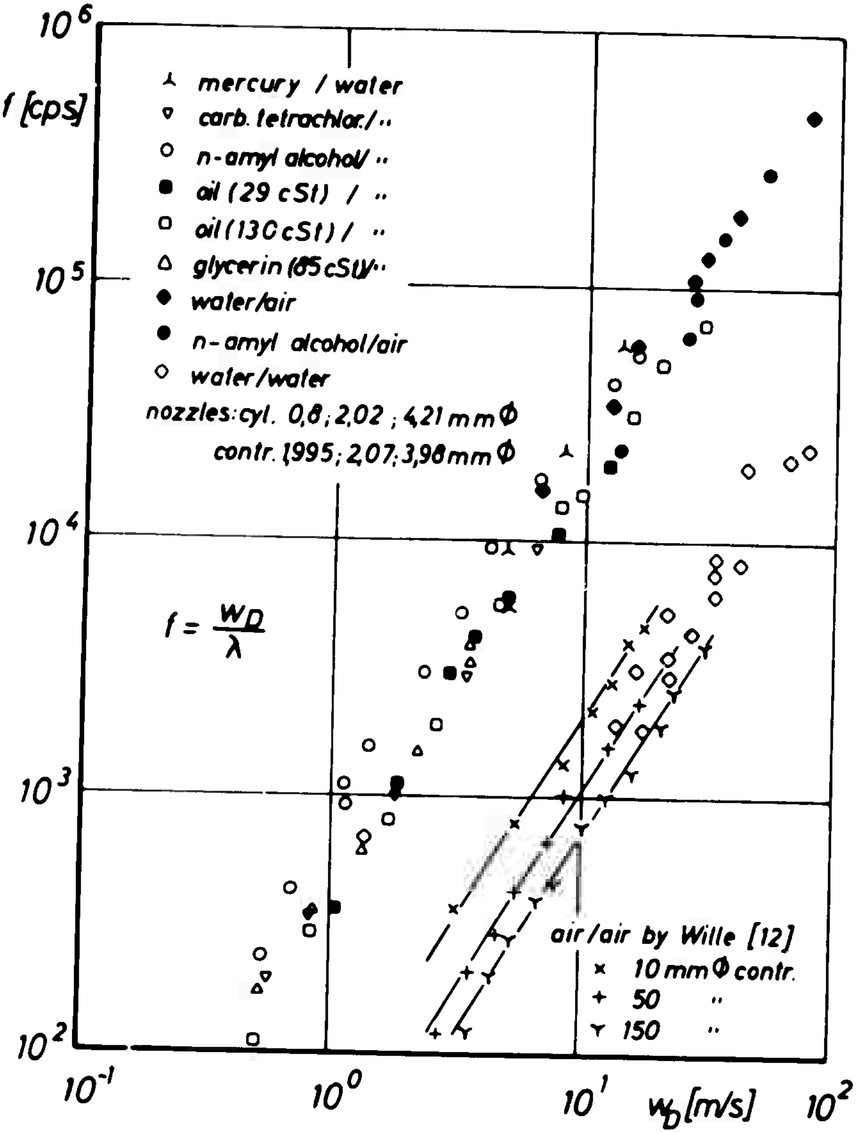

Fig.13. Disturbance frequencies

liquid particles characterizes the turbulent interface, in other words the turbulent exchange of mass. A general equation

$$\left.\frac{x}{D}\right|_{crit} \sim Re_D^{-(1 - m)/m} \qquad (18)$$

has to substitute the empiric transition law $Re_x = (3,5 - 10)\ 10^5$ of Blasius flow, taking into account that rotational symmetric two-phase flow may be arranged qualitatively between the limiting cases of longitudinal annulus flow around a cylinder (ν_1/ν_2 very large) on the one hand, and pipe flow (ν_1/ν_2 very small) on the other hand.

The special case of the plane smooth plate is included by $m = 0,5$ omitting the jet diameter. Generally the exponent varies in the range of 1/3 to 2/3, dependent on the viscosity ratio ν_1/ν_2 and the material parameter $\mu_1/\sqrt{\varrho_1 DT}$.

The waves of small amplitudes can be compared with the riples of a water surface stirred up by a soft wind; they appear only in the case of high jet velocities, small viscosity and small turbulence intensity. These frequencies, equal to the ratio of mean velocity and evaluated wave length, mount up to 100 kcps. A density ratio of about "1" increases the amplitude. All experiments aside from very low velocities led to the law

$$f \sim w_D^{3/2} \qquad (19)$$

known from subsonic gas jets and relating disturbance-(vortex-) frequency and jet velocity [12] . Fig. 13 gives a survey of the results confirming 3/2 power law in a far range of fluid properties and relative velocities. Reynolds number covering several decades, and the 2 nozzle constructions employed, correspond to an extensive variation of initial velocity profiles and therewith of initial boundary

layer thickness. The coupling of laminar or turbulent flow with disperse or continuous phase does not noticeable vary the power law, which can be proved by the exchange of the phases. The viscosity ratio must remain a feeble parameter in the two phase flow because of the break in the velocity profile in contrast to the homogeneous flow. The influence of this parameter is further reduced by interfacial tension. A relationship with the power laws of the theory of hydrodynamic stability can be pointed out.

Fig. 14 represents an example of the velocity distribution of liquid particles in the disintegration region of a water jet. The continuous phase consists of air of atmospheric pressure at normal temperature. The envelope corresponds to best fit data if the depth of focus is larger than a thin section in the plane of the jet axis. The curve resembles the Gaussian distribution. Fig. 15 is the copy of the evaluated film.

8.3. Pressure decrease and fluctuations

The homogeneous jet can be regarded to be a special case of the two phase system. No local variation of concentration accompanies the exchange of momentum. A decrease of static pressure in the mixing region was observed, deviating from known theory. First statements from some systematic experiments have the following result: A dimensionless pressure coefficient as a function of relative nozzle distance expresses the stationary pressure decrease. The maximum value corresponds to the minimum jet velocity under otherwise constant conditions just sufficient to reach vapour pressure in the mixing region. Pressure fluctuations arising in the nozzle superpose the rather regular rolling up of vortices, observable by reason of the vapour filled core. Fig.16 gives an example. There is again a relationship of fluctuation repetition rate and jet velocity. The intermittency factor may have some importance. These phenomena were studied on translucent

nozzles manufactured carefully. Some difficulties and an instationary behaviour can arise since the disperse phase often includes air bubbles of minute size.

Finally fig. 17 demonstrates the atomization cone of a swirl atomizer. This is an example for applying the high speed kinematography for a chiefly technically important purpose. Progressive waves and liquid film disintegration can be observed clearly.

a b

Fig. 12. Jet disintegration in the case of high and low turbulence of the jet; n-amyl alcohol jet into air.

a. High turbulent jet, cylindrical nozzle

b. Low turbulent jet, contracted nozzle.

Nozzle exit velocity: 40 m/s
Nozzle exit diameter: 2 mm

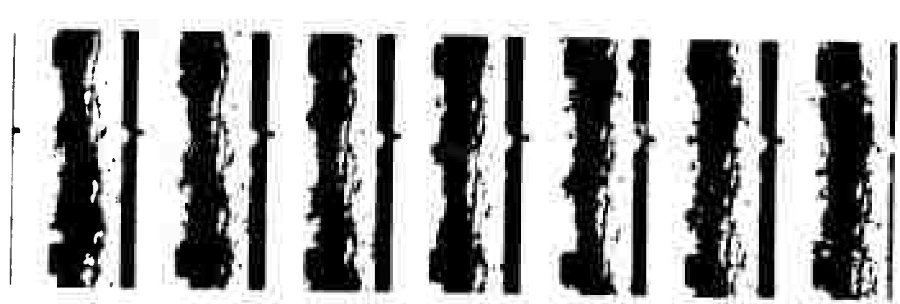

Fig. 15. Water jet into air.

Nozzle exit velocity: 56 m/s
Nozzle exit diameter: 2 mm

Shot repetition rate 10.000 pict./s.

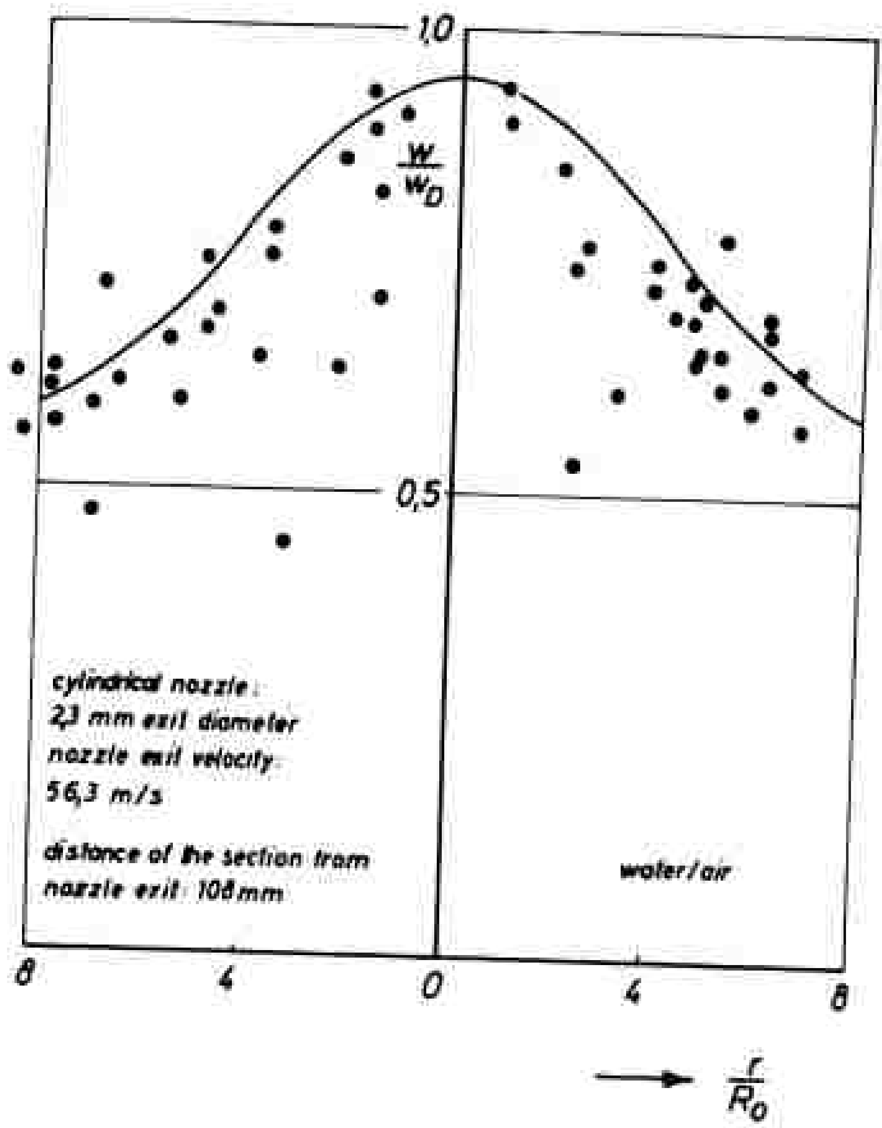

Fig. 14. Velocity distribution in the mixing region

Fig. 16. Pressure fluctuations in the homogenious system (oil).
Nozzle exit velocity: 62 m/s
Nozzle (cylindr.) exit diameter: 1 mm
Mean shot repetition rate 1200 pict/s.

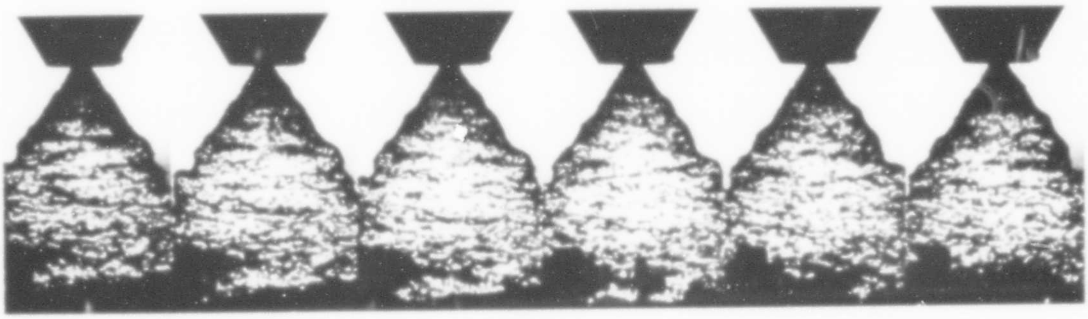

Fig. 17. Swirl atomization of water

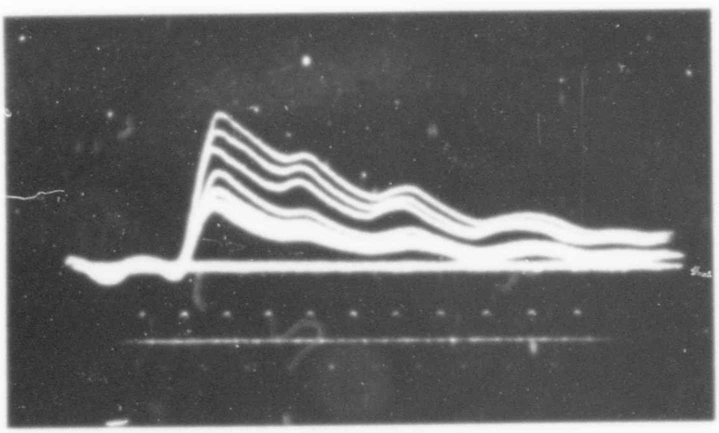

Fig. 19. Brightness of 10 shots versus time.
Shot repetition rate 1 kcps,
calibrating frequency 100 Mcps.

Appendix

Breakdown voltage with slow and fast charging, statistical jitter and the influence of repetition rates

Tests

1. This condition is established for the following tests: Breakdown voltage must be constant at least within ± 2 % in the range of 500 shots, approximately 1 cps and slow charging (i.e. slow voltage rise on the capacitor) and free firing sequences.
2. Investigation of breakdown voltage of single shots with fast voltage rise (4 kV/us). The trigger time of the oscilloscope is adjusted manually in order to get at least 15 curves on each Polaroid exposure.
3. Charging voltage and brithness characteristics of timed shot series are exposed in the range of 25 - 10 000 cps repetition rate. The observation of brightness of 100 shot series with different repetition rates is suitable to control this test.

Results

1. The breakdown voltage, when slow charging is used, can be varied by means of an adjustable radial electrode. Any disadvantages were not observed compared with a soldered radial electrode arrangement. Polishing of the electrodes is favourable in any case, although 20 to 30 shots may be necessary to attein constancy of breakdown voltage. Teflon seems to be the most suitable washer material; if no washer is used the discharge in a fixed position of the arc can only be realized with low breakdown voltage.

2. Breakdown voltage of single shots with fast charging fluctuates with ± 20 % around a mean value which surmounts the discharge voltage in the case of slow charging, see fig. 18. The resulting displacement of exposures on the running film remains so far within the circle of divergence.

3. With increasing repetition rates the breakdown voltage drops distinctly after the first shot of a series, see fig. 19. Since the trigger unit fixes the rise dU/dt physical phenomena dependent on repetition rate and shot numbers must be taken into consideration to be responsible for this observation. In the range of 1 kcps the slight charging value is attained. With increasing repetition rates the curve drops to a theoretical maximum value of a repetition rate which permits just a small voltage-less interval between the single charging pulses of 6 μs duration.

These facts permit the following conclusions of especially technical importance. Neither the breakdown voltage of the slowly charged capacitor nor the mean value of the breakdown voltage at high repetition rates present a criterion for the dielectric strenght of the pulse light source. The real maximum value of the breakdown voltage seems to depend on the rise of the charging voltage at the capacitor. The construction of the trigger unit does not permit to vary this rise. Only the first shot of a series falls into the range of high values of the breakdown voltage. The function of the brightness of the shots within a series confirms the observation.

The brightness of the first shot exceeds the value of the following ones. The discharge tends to an asymptotical behaviour taking into account the resolving power of the oscilloscope and of the exposures.

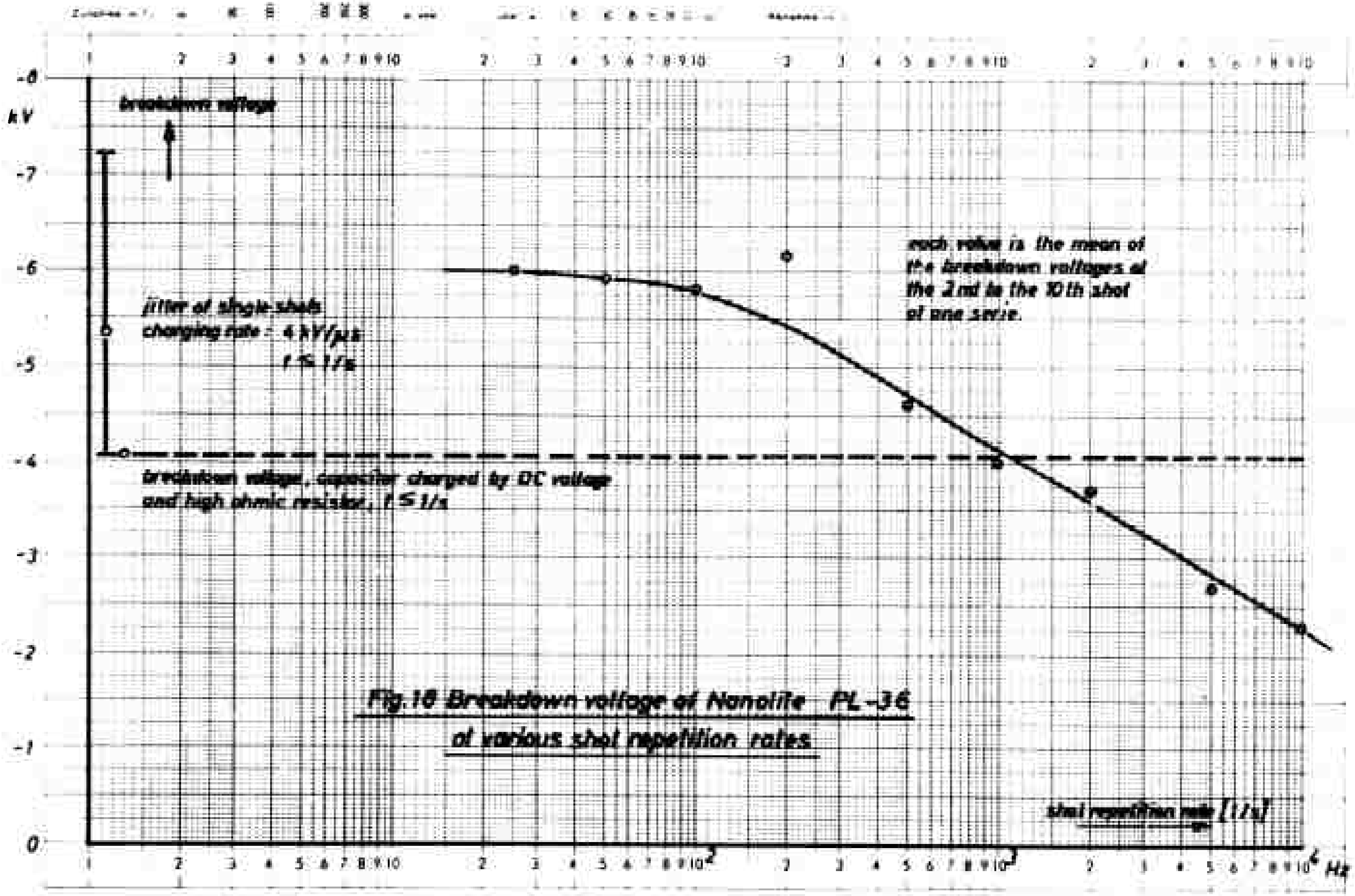

Fig.18 Breakdown voltage of Nanolite PL-36 of various shot repetition rates

Eine Achse logar. geteilt von 1 bis 10000, Einheit 62,5 mm, die andere in mm mit Prozentmaßstab

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